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BULLETIN No. 212

The Frictional Properties of Lead-base and Tin-base Bearing Alloys:

The Role of the Matrix and the Hard Particles

By

D. TABOR, Ph.D. (Cantab.)
(*Section of Tribophysics*)

MELBOURNE, 1947

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FOREWORD.

This Bulletin describes an investigation recently undertaken by the Section of Tribophysics (formerly known as the Lubricants and Bearings Section) of the Council. In the previous Bulletins in this series (Bulletins Nos. 145 and 155) a theory of metallic friction was developed, and the lubricating effect of thin metallic films was discussed and applied to an investigation of the theory of action of bearing alloys of the copper-lead type. This Bulletin is a continuation of this work, and deals with the theory of action of bearing alloys of the white-metal type.

SUMMARY.

In a previous Bulletin (No. 155) an account was given of the frictional properties of alloys of the copper-lead type which consist of a relatively hard matrix (copper) in which soft particles of lead are dispersed. As a result of the smearing of the soft phase over the hard matrix, metallic film lubrication is provided. This paper describes work on tin-base and lead-base bearing alloys which possess soft matrices in which are dispersed small hard particles; and also on special alloys consisting of the matrix material alone. Measurement of friction at room and elevated temperatures for clean and for lubricated surfaces showed that the hard particles of the bearing alloys played no great part in the basic frictional and wear properties of the alloys. The view is put forward that the frictional behaviour of a white-metal bearing alloy is a function of the properties of the matrix, although under service conditions there may be other properties which determine the suitability of the alloy for use in bearings.

The Frictional Properties of Lead-base and Tin-base Bearing Alloys:

The Role of the Matrix and the Hard Particles *

1. Introduction.

Bearings are normally designed to run with a finite film of oil separating them from the rotating journal. In such a case the frictional resistance depends on the clearance, the load, the speed, and the viscosity of the oil film. Provided the oil film is maintained, the metal surfaces of the journal and the bearing play no part, and there is no wear of either journal or bearing. In practice, however, particularly in starting and stopping, and on impact, the finite oil film may break down and only thin, "boundary", films of lubricant may remain. Under severe conditions, considerable metallic contact may occur. It is during these incidents of boundary lubrication and of metallic contact that the wear and seizure of bearings occur. It is therefore important that the frictional and wear properties of these alloys should be studied under such conditions, and that we should have a clearer understanding of the physical processes that occur during sliding.

It has been pointed out (Bowden and Tabor, 1942*c*) that one factor of great importance is the temperature of the metal surfaces. When the bearing is running, the frictional heat may cause a local softening or melting at the regions where the moving metals are momentarily in contact (Bowden and Ridler, 1936; Matthew, 1940). For this reason it is desirable that one of the constituents of a bearing metal should have a relatively low melting point, so that if excessive heating occurs the metal may melt and flow to another region and so prevent seizure.

For this reason, alloys of the copper-lead type are well suited for use in bearings. These alloys usually consist of a *hard* matrix of copper with the *soft* lead finely dispersed through it (see Plate 1, Fig. 1). The friction of these alloys is very much less than that of either of the main constituents, and it was shown (Bowden and Tabor, 1942*c*) that their frictional properties resemble very closely those of a hard surface consisting of a matrix material, over which a thin film of the softer metal has been spread.

It was suggested that bearing alloys of this type act by the extrusion and smearing of a thin film of a soft low-melting constituent over the surface of a harder matrix. The hard surface takes the load, whilst the actual sliding takes place on the thin film of the softer metal, thus causing a great reduction in friction (Bowden and Tabor, 1942*b*). With excessive loading or heating the surface film of the softer metal will melt and flow to another portion of the surface, so reducing the chances of seizure and the wear, whilst the mechanical properties of

* Typescript received March 5, 1946. A condensed account of part of this work has appeared in *J. Appl. Phys.* **16**: 325 (1945).

the matrix material may be little affected. In this way the extruded softer constituent may play a fundamental part in reducing the friction, wear, and seizure between the sliding surfaces.

It is clear, however, that this explanation is not applicable to all types of bearing alloys. A large class of bearing alloys (e.g., "white-metal" bearings) possess a duplex structure, consisting of *hard* crystals embedded in a relatively *soft* matrix (see Plate 1, Fig. 2, and Plate 5, Fig. 1). In these alloys the soft matrix forms the continuous phase, and it is clear that the isolated hard crystallites cannot bear the load in the same way as the copper matrix of a copper-lead alloy.

It has indeed been suggested (Desch, 1937) that the function of the hard crystals is to resist wear, and that of the softer constituents to permit a more uniform distribution of the load, by allowing any of the hard crystals that are heavily loaded to sink, so that the load is spread over a greater area. Other workers on the other hand (see Bassett, 1937) have suggested that the hard particles play little part in the frictional properties of the alloys, though this view has not been widely accepted. A further discussion of these and other theories is given by Bassett and by Desch. It is evident that the mechanism of this type of white-metal bearing alloy is by no means certain.

This Bulletin describes experiments carried out on a typical tin-base and lead-base bearing alloy. Their frictional behaviour has been investigated at room temperature and at elevated temperatures, in the presence and in the absence of lubricant. In order to obtain further evidence on the respective roles of the matrix and the hard crystallites, special "matrix" alloys were prepared, consisting of the matrix material only, and their properties compared with those of the bearing alloys. It should, however, be emphasized that these "matrix" alloys are only approximations to the complex phase relationships existing in their respective bearing alloys. Frictional measurements were also made, using pure lead and pure tin

It is emphasized that in this paper the investigation is confined to the basic frictional properties of the alloys under clearly-defined experimental conditions of load, speed, &c. It is, of course, evident that in practice the suitability of an alloy is not only determined by its frictional and wear properties. Many of its physical properties may play a vital part in determining its performance in a running engine. The present investigation does, however, indicate that the general theory of certain white-metal bearing alloys needs to be reconsidered.

2. Experimental.

The apparatus was similar in design to that described in earlier papers (Bowden and Leben, 1939, 1940). The upper surface was in the form of a hemispherical slider, whilst the lower surface was in the form of a flat plate, which was driven forward at a uniform rate by a water piston. The upper surface, which has a certain degree of freedom, was supported by a spring device for applying the load and a bifilar suspension for measuring the frictional force. Since the inertia of the system is small, it is capable of responding readily to any rapid fluctuations in the frictional force which may occur between the sliding surfaces. The deflection of the arm carrying the upper surface is a measure of the frictional force, and this is recorded optically by a

moving film camera. The design of the apparatus is such that the speed and temperature of the surfaces and the friction are all automatically recorded on the camera film.

The flat steel surface was finely ground and made optically flat by specially prepared lead laps impregnated with carborundum of standard size. They were washed and carefully cleaned with rouge, and were finally degreased in a vapour bath of benzene and alcohol. The surfaces of the soft metals were cleaned by fine scraping or by turning with a dry clean tool on the lathe without the use of cutting fluid. Some specimens were polished and etched, as for metallographic examination, and then thoroughly washed and allowed to dry before use.

Each combination was usually tested in two ways: firstly with one metal as the upper curved surface, and then with the metals interchanged. In all these experiments the speed of sliding was low; it varied from 0·01 to a few centimetres per second, so that the surface temperature of the metals was sensibly the same as their bulk temperature.

3. Types of Sliding.

The frictional measurements show that the sliding may proceed in intermittent jerks (stick-slip motion), or it may be smooth. When stick-slip motion occurs, the upper slider welds on to the lower surface and moves with it until the restoring force exceeds the strength of the metallic junctions formed, and slip occurs. The slider seizes again at the next stick, and the behaviour is repeated. With surfaces moving extremely slowly, the friction at the stick (referred to as μ_{max}) is the co-efficient of static friction and is a measure of the tendency of the surfaces to seize. The amplitude and frequency of the slip depend on many factors, such as the natural frequency, the moment of inertia, and the damping of the moving parts, as well as on the load and speed (Bowden, Leben, and Tabor, 1939). Recent investigations by Sampson, Morgan, Reed, and Muskat (1943) have also shown that the frictional behaviour during the slip is very complex. However, with a system that is not heavily damped, the mean friction (referred to as μ_{mean}) is approximately equal to the kinetic friction of the surfaces at surface speeds above a few cm./sec. The value of μ_{mean} given in the following tables may therefore be considered as a measure of the kinetic friction; it also serves as an additional point of comparison between the respective bearing and matrix alloys.

Stick-slip motion necessarily implies that the static friction is higher than the kinetic friction. For this type of motion the track on the lower surface consists of intermittent smears or gashes corresponding to the seizure of the surfaces at each stick.

Smooth sliding occurs when there is no marked difference between the static and kinetic friction. There is a continuous shearing and seizing of metallic junctions. The corresponding track on the lower surface consists of a continuous smear or groove.

4. The Frictional Behaviour of Lead-base Alloys.

(i) *Materials.*

The bearing alloy under investigation (designated lead bearing alloy) had the following composition:—Antimony 15·0 per cent., copper 0·5 per cent., tin 6·0 per cent., and lead 78·5 per cent.

The microstructure is shown in Plate 1, Fig. 2, and it is seen that the alloy consists of a lead-tin-antimony eutectic (possessing a fine duplex structure), in which are dispersed the hard cuboids of tin-antimony compound. The dark areas surrounding the cuboids consist of a lead-rich solid solution. The matrix consists of the eutectic and the solid solution.

A special microhardness apparatus was constructed for measuring the hardness of the various phases of the alloys investigated. The indentor consisted of a finely-polished pyramidal diamond, and the load used was between 0·3 and 1 g. The diamond left a well-defined impression in the surface of the metal of diameter between 10^{-3} and 10^{-4} cm. The apparatus was calibrated by making similar impressions in pure metals of known hardness. This method gave results reproducible to a few per cent.

With the lead bearing alloy, microhardness measurements showed that the matrix material had a hardness of approximately 19, while the cuboids had a hardness of over 110 in equivalent Vickers units. The mean (macroscopic) hardness, as measured on the Vickers machine, was 21.

The lead bearing alloy was compared with a matrix alloy (designated as lead "matrix" alloy) possessing the following composition:— Antimony 10 per cent., lead 87 per cent., tin 3 per cent., and copper 0 per cent. The microstructure is shown in Plate 1, Fig. 3, and it will be seen that it consists of dendrites of lead-rich solid solution set in a duplex matrix of lead-tin-antimony eutectic. There are no hard particles present, and the structure approximates to that of the matrix material of the lead bearing alloy. Microhardness measurements on the matrix alloy show that the lead-rich dendrites and the lead-tin-antimony eutectic are of equal hardness to within a few per cent., the Vickers hardness being ca. 18.

The hardness values of the metals used are summarized in Table 1, and as a matter of interest the hardness of a typical non-dendritic copper-lead alloy is included.

Table 1.

Material.	Macroscopic Hardness (Vickers).	Microhardness in Equivalent Vickers Units.
Pure lead	4	
Lead bearing alloy	21	Matrix 19 Cuboids 110
Lead matrix alloy	18	Lead-rich solid solution 18 Duplex Pb-Sn-Sb eutectic 18
Steel	166	
Copper-lead alloy	35	Copper matrix 56 Lead phase 8

(ii) *The Friction of Unlubricated Surfaces.*

The frictional results are given in Table 2. It is seen that the sliding of the softer metals on the steel surface proceeds in stick-slips; the sliding of steel on the softer metals is relatively smooth.

TABLE 2.—FRICTION OF STEEL, LEAD, AND LEAD ALLOYS, UNLUBRICATED.

Surface.	$\mu_{max.}$	$\mu_{mean.}$	Type of Motion.
Steel on lead	0·9–1·0	0·9–1·0	Fairly smooth
Steel on lead bearing alloy	0·4–0·45	0·35	Small stick-slips
Steel on lead matrix alloy	0·35–0·4	0·35–0·4	Smooth
Lead on steel	0·9	0·5	Very large stick-slips
Lead bearing alloy on steel	0·5–0·55	0·35–0·4	Stick-slips
Lead matrix alloy on steel	0·65–0·7	0·4	Large stick-slips

The tracks on the steel surface consisted of intermittent smears. The tracks formed on the softer metals consisted of well-defined grooves, within which the material was badly torn. In order to show up the nature of the track for the bearing alloy, the surface was polished and etched before the run. Part of the track is shown in Plate 2, Fig. 1, side by side with the unworn portion of the surface. It is clear that the structural arrangement of the crystallites has been obliterated by the passage of the steel slider.

A similar track for the lead matrix alloy is shown in Plate 2, Fig. 2, and it is clear that the surface has been badly torn by the passage of the steel slider.

It is at once apparent that the frictional behaviour of the lead bearing alloy is very similar to that of the lead matrix alloy. The type of sliding, the actual values of μ, and the appearance of the track are very much alike. The behaviour is also similar to that of pure lead, except that the friction of the lead-base alloys is appreciably less.

(iii) *The Effect of Repeated Sliding Over the Same Track.*

The slider was run over the same track several times in succession, and the friction recorded. In some cases, the track was photographed.

The results for lead are summarized in Table 3.

TABLE 3.—EFFECT OF REPEATED SLIDING OVER THE SAME TRACK ON LEAD.

Surface.	Co-efficient of Friction $\mu_{max.}$		
	1st Run.	20th Run.	100th Run.
Steel on lead	1·2	1·4	..
Steel on lead bearing alloy ..	0·4	0·7	..
Steel on lead matrix alloy	0·4	0·8	..
Lead on steel	0·9	1·0	..
Lead bearing alloy on steel	0·5	0·75	0·95
Lead matrix alloy on steel	0·7	1·1	1·2

It is seen that there is no appreciable change in friction for the pure lead surface. The track becomes more marked with each successive traverse, but otherwise the general appearance remains unaltered. Although the tracks for the alloys also show little change in appearance with each successive traverse, they show, on the other hand, a marked increase in friction. The first run gives a friction of about $\mu = 0{\cdot}4$–$0{\cdot}5$, whilst the twentieth run gives a value of about $\mu = 0{\cdot}8$. The reason for this rise is not clear, but it is evident that the frictional behaviour of the lead bearing alloy and of the lead matrix alloy are very similar with respect to wear.

(iv) *Wear of the Alloys on Steel.*

The wear properties of the alloys were compared by the following method:—The upper surface was made of the alloy, and the lower surface of steel. The upper surface was run over the lower surface repeatedly for 400 runs (corresponding to a total track length traversed of 3,000 cm. It was then weighed and the loss in weight determined.

The friction was also observed during the runs. The surfaces were unlubricated. The amount of wear and the main friction results are summarized in Table 4.

TABLE 4.—WEAR OF LEAD-BASE ALLOYS ON STEEL, UNLUBRICATED.

Surface.	Co-efficient of Friction μ_{max}.			Wear after Traversing 3,000 cm. of Track. mg.
	1st Run.	100th Run.	400th Run.	
Lead bearing alloy	0·55	1·0	1·0	11
Lead matrix alloy	0·7	1·2	1·2	14

During the sliding process the alloy welds on to the steel surface. This is shown by an examination of the tracks formed by the alloys on the steel surface. Photomicrographs of the tracks after 400 runs are shown in Plate 2, Figs. 3 and 4. It is seen that the smearing of alloy on to the steel surface has been so marked that the lapping marks on the steel have been completely obliterated.

It is evident that the friction and wear behaviour of both the lead alloys is similar, and that the actual values of the wear are of the same order.

(v) *Effect of Temperature.*

The following experiments were carried out with the steel slider as the upper surface. The temperature of the lower surface was gradually raised to 200°C., and a continuous record of the friction and the surface temperature was made. When the run was completed the track width was measured at various points in the run. As the square of the track width is an approximate measure of the area of contact, which in turn is a measure of the hardness, this provides a method of following the way in which these quantities vary during the course of the run (Bowden and Tabor, 1942*c*).

The variation of the co-efficient of friction, μ_{max}, with temperature for pure lead and for the lead alloys is shown in Fig. 1, and the variation of the square of the track width in Fig. 2.

From Fig. 1 it is seen that the pure lead and the two alloys behave similarly; their friction is almost independent of temperature. Fig. 2 shows that pure lead is very much softer than the alloys, but that the hardness and the variation of hardness with temperature of the two alloys are very similar.

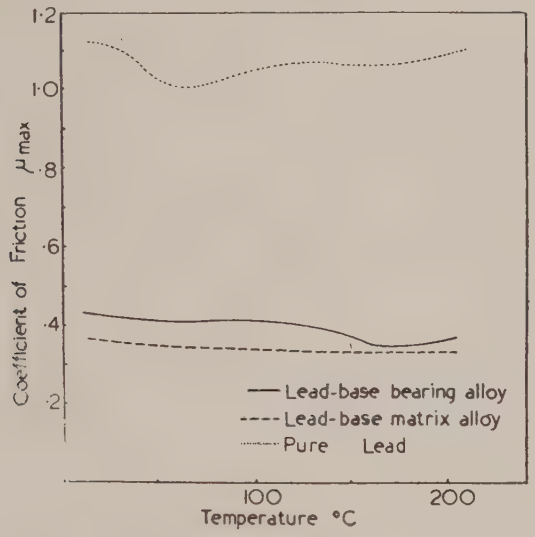

Fig. 1. Variation of friction with temperature for lead, and lead-base alloys.

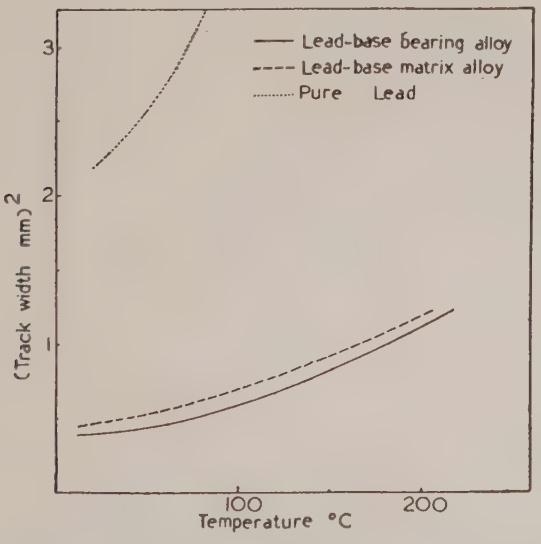

Fig. 2. Variation of square of track width with temperature for pure lead and lead-base alloys. The square of the track width is a measure of the reciprocal of the hardness.

(vi) *Surfaces Lubricated with Mineral Oil.*

In these experiments the lubricant used was a refined mineral oil, and was applied as a thin smear. The friction results are given in Table 5.

TABLE 5.—FRICTION OF LEAD-BASE ALLOYS LUBRICATED WITH MINERAL OIL.

Surface.	$\mu_{max.}$	$\mu_{mean.}$	Type of Motion.
Steel on lead	0·5	0·3	Large stick-slips
Steel on lead bearing alloy	0·12	0·12	Smooth sliding
Steel on lead matrix alloy	0·14	0·14	Smooth sliding
Lead on steel	0·4	0·22	Large stick-slips
Lead bearing alloy on steel	0·32	0·18	Large stick-slips
Lead matrix alloy on steel	0·35	0·2	Large stick-slips

It is seen that the frictional behaviour of the bearing alloy is very similar to that of the matrix alloy. The friction of both alloys is lower than that of pure lead. This is particularly marked when the upper surface is of steel.

When the upper surface is of steel the track formed in the alloy consists of a well-defined groove. If the alloys are prepared by polishing and etching, the track may be shown up clearly against the unworn portion of the surface. A typical track for the lead bearing alloy is shown in Plate 3, Fig. 1, and for the lead matrix alloy in Plate 4, Fig. 1. It is clear that for both alloys the crystalline structure of the surface has been little disturbed by the passage of the steel slider.

(vii) *Effect of Repeated Sliding Over the Same Track, Lubricated Surfaces.*

Continuous traversals of the same track do not produce any marked change in the friction, as is seen in Table 6.

Examination of the tracks shows that as the slider passes repeatedly over the same track, the amount of tearing and smearing increases cumulatively, and the surface structure of the alloys is increasingly disturbed.

TABLE 6.—REPEATED SLIDING OVER SAME TRACK, LUBRICATED SURFACES.

Surface.	Co-efficient of Friction $\mu_{max.}$		
	1st Run.	20th Run.	100th Run.
Steel on lead	0·5	0·5+	..
Lead bearing alloy	0·12	0·12	0·11
Lead matrix alloy	0·14	0·15	0·17

With the lead matrix alloy, after the twentieth run, the arrangement of the surface structure is almost completely obliterated (Plate 4, Fig. 2). With the lead bearing alloy, the tin-antimony crystallites are still clearly visible after the twentieth run, but after the 100th run they have been almost entirely obliterated (Plate 3, Figs. 2 and 3). Never-

theless, the surface damage of the alloys is greatly reduced by the presence of the lubricant, and there is relatively little tearing of the surface. The amount of pick-up on the steel slider must also be very small. This accounts for the fact that the friction does not increase appreciably with wear, in marked contrast to the observations described for clean surfaces. It is apparent that the area of contact remains essentially unchanged and the junctions formed are still of the same nature as in the first run.

(viii) *Effect of Temperature, Lubricated Surfaces.*

The effect of temperature on the boundary lubricating properties of lubricants has been discussed in earlier work (Tabor, 1940, 1941). The breakdown of the lubricant is associated with a melting or disorientation of the protective film formed by the lubricant on the metal surfaces. It is markedly dependent on the composition and structure of the sliding surfaces (Hughes and Whittingham, 1942; Gregory, 1943).

The effect of temperature on the friction of steel sliding on pure lead and the lead-base alloys lubricated with mineral oil is shown in Fig. 3. The results when the surfaces are lubricated with stearic acid are shown in Fig. 4. In these experiments the metal surfaces were heated to about 70°C.; a few crystals of stearic acid were added (M.P. 68°C.), and the surfaces allowed to cool to room temperature. There is again a close similarity in behaviour of both alloys.

5. The Frictional Behaviour of Tin-base Alloys.

(i) *Materials.*

The bearing alloy under investigation (designated tin bearing alloy) had the following composition:—Antimony 6·5 per cent., copper 4·2 per cent., tin 89·2 per cent., and nickel 0·1 per cent. Its mean hardness was 24 (Vickers). The microstructure, shown in Plate 5, Fig. 1, shows that it consists of a matrix of a tin-rich solid solution, in which are embedded numerous hard needles of copper-tin compound. This alloy was compared with pure tin, and also with a tin-base matrix alloy, containing 7 per cent. antimony, no nickel, and less than 0·4 per cent. copper. The microstructure is shown in Plate 5, Fig. 2, and it is seen that it consists of a tin-rich solid solution: it contains no hard particles, and in hardness and structure is similar to the matrix material of the tin-base bearing alloy. The main hardness values are given in Table 7.

Table 7.

Material.	Macroscopic Hardness (Vickers).	Microhardness in Equivalent Vickers Units.
Pure tin	7	7
Tin bearing alloy	24	Matrix ~ 20 Needles > 100
Tin matrix alloy	18	18

However, the tin matrix alloy did not appear to be as close an approximation to the matrix of the bearing alloy as was the case with the corresponding lead-base alloys.

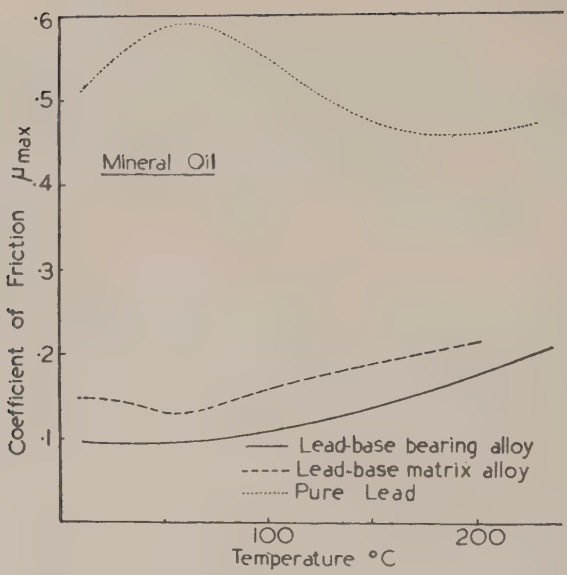

Fig. 3. Variation of friction with temperature for steel sliding on pure lead and lead-base alloys; lubricated with mineral oil.

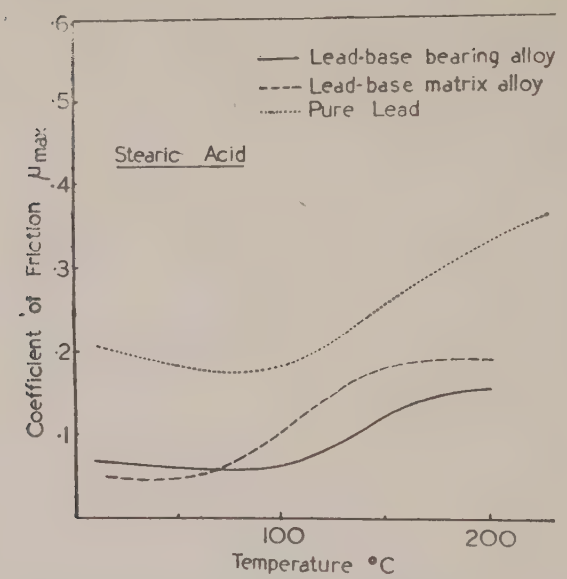

Fig. 4. Variation of friction with temperature for steel sliding on pure lead and lead-base alloys; lubricated with stearic acid.

(ii) *The Friction of Unlubricated Surfaces.*

All the surfaces tested gave large stick-slip motion when clean. The main friction results are assembled in Table 8.

Table 8.—Friction of Steel, Tin, and Tin-base Alloys, Unlubricated.

Surface.	$\mu_{max.}$	$\mu_{mean.}$	Types of Motion.
Steel on tin	0·9	0·6	Large stick-slips
Steel on tin bearing alloy ..	0·7	0·45	Fairly large stick-slips
Steel on tin matrix alloy ..	0·7–0·8	0·45	Fairly large stick-slips
Tin on steel	0·8	0·5	Large stick-slips
Tin bearing alloy on steel ..	0·7	0·4	Large stick-slips
Tin matrix alloy on steel ..	0·8	0·4	Large stick-slips

These results show that the friction of the tin bearing alloy and the tin matrix alloy are very similar. In both, the friction of the alloys is about 20 per cent. less than the friction of pure tin.

The tracks on the steel surface consisted of intermittent smears. The tracks formed on the softer metals by the steel slider consisted of well-defined grooves, within which the material was badly torn. The nature of the track for the alloys is shown more clearly when the surfaces are polished and etched before the run. Part of the track for the bearing alloy is shown in Plate 6, Fig. 1, and it is clear that the structural arrangement of the hard needles has been obliterated by the passage of the steel slider. A similar track for the matrix alloy is shown in Plate 6, Fig. 2, and again there is marked evidence of tearing and smearing of the surface.

It is at once apparent that both the value of the friction and the appearance of the track are similar for the tin bearing alloy and the tin matrix alloy.

(iii) *The Effect of Repeated Sliding Over the Same Track.*

The main frictional results are summarized in Table 9.

Table 9.—Effect of Repeated Sliding Over the Same Track.

Surface.	Co-efficient of Friction $\mu_{max.}$		
	1st Run.	20th Run.	100th Run.
Steel on tin	0·9	0·9	..
Steel on tin matrix alloy	0·7–0·8	0·65–0·8	..
Steel on tin bearing alloy	0·7–0·8	0·85	..
Tin on steel	0·8	0·9	..
Tin bearing alloy on steel	0·7	0·8	0·8
Tin matrix alloy on steel	0·8	0·85	1·2

These results show that there is no appreciable change in friction for the pure tin and the tin alloys for the first twenty runs. The tracks also show little change in appearance with wear. The tin-base alloy shows a more marked increase of friction for 100 runs. Apart from this the frictional behaviour of pure tin, of the tin bearing alloy, and of the tin matrix alloy are very similar with respect to wear.

(iv) *The Wear of the Alloys on Steel.*

The wear properties of the alloys were compared for 400 traversals of the same track (total track length 3,000 cm.) on a clean steel surface. The wear of the tin bearing alloy was extremely small, of the order of 0·2 mg. The worn portion was clearly burnished, and the edges of the worn area were clearly defined. With the tin matrix alloy, the wear was also very small, about 0·3 mg. There was a very slight peeling of the worn material adhering to the surface, and when removed the total wear amounted to 0·7–0·8 mg. The amount of wear and the main friction results are summarized in Table 10.

TABLE 10.—WEAR OF TIN-BASE ALLOYS ON STEEL, UNLUBRICATED.

Surface.	Co-efficient of Friction μ_{max}.			Wear after Traversing 3,000 cm. of Track.
	1st Run.	100th Run.	400th Run.	
				mg.
Tin bearing alloy ..	0·7	0·8	0·6	0·2
Tin matrix alloy ..	0·8	1·2	1·0	0·3–0·7

The tracks formed by these alloys after 400 runs are shown in Plate 6, Figs. 3 and 4. It is seen that there is marked smearing of the alloys on the steel, but that the lapping marks on the steel are visible through the track. It is evident that the transfer of metal on to the steel surface is far less marked than with the lead-base alloys.

These measurements show that the wear behaviour of both the tin alloys is similar, and the actual values of wear are of the same order.

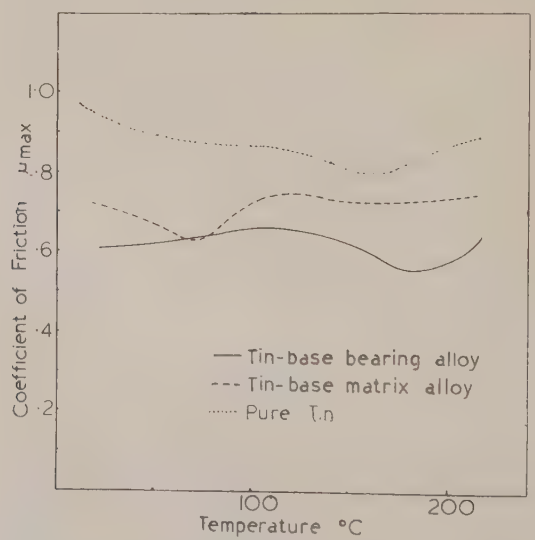

FIG. 5. Variation of friction with temperature for pure tin, and tin-base alloys.

(v) *The Effect of Temperature.*

The variation of μ_{max} with temperature for pure tin and for the tin alloys is shown in Fig 5, and the variation of the square of the track width in Fig. 6. It is again apparent that for pure tin and the tin-base alloys the friction is almost independent of temperature. Further, the hardness and the variation of hardness with temperature of the tin bearing alloy are very similar to those of the tin matrix alloy.

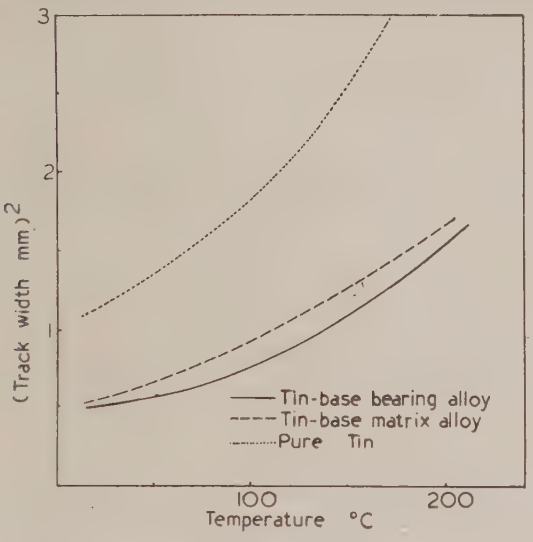

Fig. 6. Variation of square of track width with temperature for pure tin and tin-base alloys. The square of the track width is a measure of the reciprocal of the hardness.

(vi) *Surfaces Lubricated with Mineral Oil.*

The same mineral oil was used as with the lead-base alloys. It was applied as a thin smear. The friction results are given in Table 11.

Table 11.—Friction of Tin and Tin-base Alloys, Lubricated with Mineral Oil.

Surface.	$\mu_{max.}$	$\mu_{mean.}$	Type of Motion.
Steel on tin	0·6	0·35	Large stick-slips
Steel on tin bearing alloy	0·13	0·13	Smooth sliding
Steel on tin matrix alloy	0·13	0·13	Smooth sliding
Tin on steel	0·36	0·17	Large stick-slips
Tin bearing alloy on steel	0·35	0·16	Large stick-slips
Tin matrix alloy on steel	0·4	0·2	Large stick-slips

It is again apparent that the frictional behaviour of the tin bearing alloy is similar to that of the tin matrix alloy. The friction of both alloys is, on the whole, lower than that of pure tin.

The deformation of the surface of the alloys when the steel surface slides over it is shown in Plate 7, Fig. 1, and Plate 8, Fig. 1. The surfaces were polished and etched before the run, and it is clear that the crystalline arrangement of the surfaces has been little disturbed by the passage of the slider.

(vii) *Effect of Repeated Sliding Over the Same Track, Lubricated Surfaces.*

The main friction results are summarized in Table 12. It is evident that the friction does not increase appreciably with wear for the tin surface and for both the tin-base alloys.

TABLE 12.—EFFECT OF REPEATED SLIDING OVER THE SAME TRACK. TIN AND ALLOYS LUBRICATED WITH MINERAL OIL.

Surface.	Co-efficient of Friction μmax.		
	1st Run.	20th Run.	100th Run.
Steel on tin	0·6	0·6	..
Tin bearing alloy	0·13	0·13	0·1
Tin matrix alloy	0·13	0·13	0·12

The central portions of the tracks formed in the tin bearing alloy for the twentieth and hundredth runs, respectively, are shown in Plate 7, Figs. 2 and 3. It is seen that the arrangement of the copper-tin needles is gradually obliterated by the repeated traversals of the steel slider.

The track formed in the tin matrix alloy for the twentieth run is shown in Plate 8, Fig. 2. The structure of the surface has been completely obliterated by the passage of the steel slider.

(viii) *Effect of Temperature, Lubricated Surfaces.*

The effect of temperature on the friction of steel sliding on tin and the tin-base alloys when lubricated with the mineral oil is shown in Fig. 7. It is clear that the frictional behaviour of the tin bearing alloy is similar to that of the tin matrix alloy, except that the friction with the bearing alloy is lower, particularly at elevated temperatures.

The results obtained for surfaces lubricated with stearic acid are shown in Fig. 8. It is seen that the behaviour of the tin matrix alloy is intermediate between that of pure tin and of the tin bearing alloy.

6. Discussion.

(i) *The Friction of Unlubricated Surfaces.*

It is at once apparent that the frictional behaviour of the bearing alloys is very similar to that of the corresponding matrix alloy. The type of sliding, the actual values of μ, and the appearance of the tracks

are very much alike. The behaviour is also similar to that of the pure main constituent, except that the friction of the lead-base alloys is appreciably less than that of pure lead.

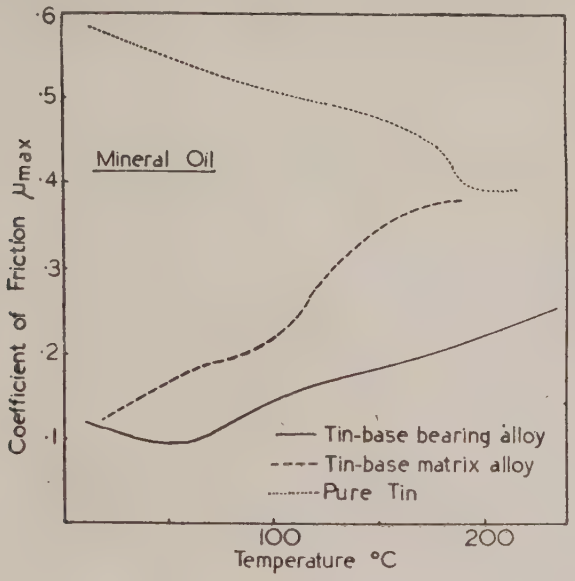

Fig. 7. Variation of friction with temperature for steel sliding on pure tin and tin-base alloys; lubricated with mineral oil.

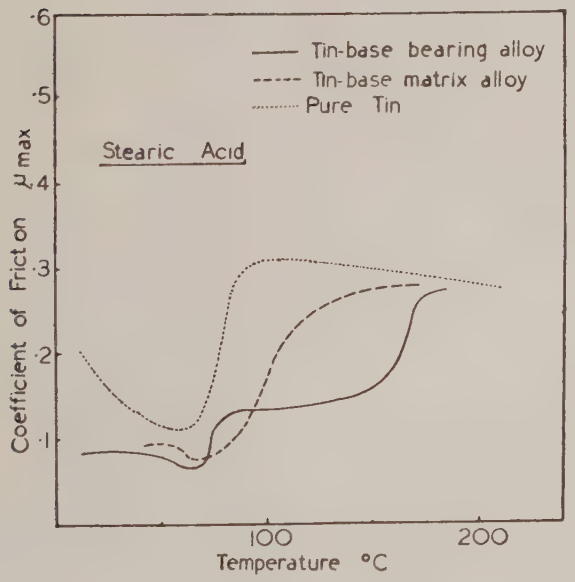

Fig. 8. Variation of friction with temperature for steel sliding on pure tin and tin-base alloys; lubricated with stearic acid.

As has been shown in earlier work (Bowden and Tabor, 1942*a*), the frictional resistance between sliding surfaces is due primarily to the shearing of metallic junctions formed at the points of contact, and to the force required to drag or plough the surface irregularities of the harder surface through the softer one. The frictional force may thus be written as—

$$F = S + P \qquad (1)$$

where S is the force of shearing, and P the force of ploughing. If the ploughing force is small, the frictional resistance may be expressed as—

$$F = S = As \qquad (2)$$

where A is the real area of contact between the metals and s is the shear strength of the metallic junctions. In the earlier work, it was shown that if there is good adhesion between the sliding surfaces, the shearing occurs within the softer metal itself, and s then corresponds to the shear strength of the softer metal, so that—

$$\text{Friction} = (\text{real area of contact}) \times (\text{shear strength of softer metal}) \qquad (3)$$

The real area of contact A is determined primarily by the load W and the "flow-pressure" p of the softer metal. When the load is applied to the surfaces, plastic flow of the softer metal occurs at the regions of contact until the area of contact is sufficient to support the applied load, and we have—

$$A = W/p \qquad (4)$$

With steel sliding on a softer metal, therefore, the softer metal flows until the area of real contact is given by equation (4). If the surfaces are clean, welded metallic junctions will form over the whole of this area. The frictional force (neglecting the ploughing term) is then equal to the force required to shear these metallic junctions, and is given by equation (3). As the shearing occurs within the softer metal there will be considerable tearing and smearing of the softer surface.

This theory of metallic friction clearly applies to homogeneous metals, such as pure lead, pure tin, &c., where the shearing takes place in the same material that supports the load. In such cases the co-efficient of friction may be expressed as the ratio of the shear strength to the flow-pressure of the metal.

With non-homogeneous alloys the friction behaviour may be different. For example, the typical copper-lead alloy shown in Plate 1, Fig. 1, consists of two distinct phases: a hard copper matrix (Vickers hardness 56) and dispersed islands of soft lead (Vickers hardness about 8). During sliding the lead is squeezed out and smeared over the copper matrix. The copper takes the load, giving a relatively small area of contact A, and the shearing occurs within the thin film of extruded lead of low shear strength s. As a result, extremely low co-efficients of friction may be obtained. The smeared lead is clearly visible in the track, and if it is dissolved with a gentle etchant, the original structure of the copper matrix is still discernible.

On the other hand, the lead matrix alloy shown in Plate 1, Fig. 3, also consists of two phases, but microhardness tests show that both these phases are of almost equal hardness. Examination of the track formed

during sliding shows that there is no preferential smearing of one phase over the other. The alloy as a whole welds on to the steel and is torn and smeared during the run, while the whole of the structure of the alloy is completely disturbed by the passage of the steel slider. It is evident that shearing takes place in the same material that supports the load, namely, the whole of the alloy. From the frictional point of view, therefore, the lead matrix alloy behaves as a homogeneous material. The same applies to the tin matrix alloy.

With the bearing alloys, the tracks show that the arrangement of the hard crystallites has been obliterated by the passage of the steel slider. It is clear that the matrix material has been smeared over the surface. This observation, and the fact that the value of the friction and the type of sliding are very similar to those of the matrix alloy, suggest that the metallic junctions producing the frictional resistance consist of the matrix material itself.

The microstructures show that the bearing alloys consist of a relatively soft matrix, in which are embedded a large number of small hard crystallites. Since the soft matrix is the continuous phase, it is clear that the crystallites cannot contribute appreciably to the hardness of the alloys: the hardness (and flow-pressure) must be determined essentially by the hardness of the matrix itself. This view is confirmed by the microhardness tests, which show that the hardness of the matrix material is almost the same as the macroscopic hardness of the alloy as a whole. It should also be noted that the hardness of the matrix alloy is similar to, though somewhat less than, that of the bearing alloy. Further, the variation of hardness (or flow-pressure) with temperature, as shown in Figs. 2 and 6, is similar. It follows that in the bearing alloys the load is taken essentially by the matrix.

These observations suggest that the action of the bearing alloys is essentially the same as that applying to the pure metals and to the matrix alloys, viz., the shearing takes place in the same material that supports the load. In this case it is the matrix material of the alloys.

(ii) *Effect of Temperature.*

This view is confirmed by the fact that the friction is almost independent of the temperature for the bearing alloys, as well as for the matrix alloys and the pure metals. This is a general result for all homogeneous metals (Bowden and Hughes, 1939; Bowden and Tabor, 1942*b*). As the temperature is raised the flow-pressure p decreases, so that the area of contact A (and hence the track width) increases. This is accompanied, however, by a corresponding decrease in the shear strength of the metallic junctions, so that the resultant frictional force observed ($F = As$) is almost constant.

This result should be compared with that observed for a typical non-dendritic copper-lead alloy, where the friction decreases as the temperature rises (Bowden and Tabor, 1942*c*). In this case the copper matrix which takes the load retains its hardness to a large extent, so that the area of contact A remains essentially unchanged. On the other hand, the extruded lead film softens with increasing temperature, so that the shear strength s decreases. As a result the friction given by As decreases with increasing temperature.

(iii) *The Effect of Repeated Sliding Over the Same Track.*

For pure metals, when the same track is traversed a number of times, there is, as has been pointed out in earlier papers, no marked change in friction. The area of contact is essentially unaltered, and the metallic junctions formed are of the same nature as in the first run.

The same behaviour is observed with the tin-base alloys. The friction is similar to that of pure tin, and there is no appreciable increase of friction with wear.

The lead alloys behave differently. The friction for the first run is of the order of $\mu = 0{\cdot}4$–$0{\cdot}5$, whilst for the twentieth run the friction increases to about $\mu = 0{\cdot}8$. The reasons for this increase are not certain. It may be due to a work hardening of the surface layers, which would increase the shear strength of the metal junctions without appreciably reducing the area of contact. If such were the case, however, a similar effect might be expected with the tin-base alloys. The effect may be due to the cumulative pick-up of the alloy on the steel surface, which results in more intimate contact between the sliding surfaces. This is confirmed by the fact that with further traversals of the same track, the friction approaches the value of the alloy sliding on itself.

These results again show in general the marked similarity in frictional behaviour of the bearing alloys and their corresponding matrix alloys.

(iv) *The Wear of the Alloys on Steel.*

The wear results described in Tables 4 and 10 show again the similarity in behaviour of the bearing alloys and the corresponding matrix alloys. In these experiments the slider consisted of the alloy and the lower surface was the flat steel plate. No lubricant was used. During sliding the alloy welds on to the steel surface. If the metallic junctions formed are firmly attached to the steel surface, the shearing occurs within the material of the slider, and small fragments of the alloy are left adhering to the steel. With repeated traversals, the process is repeated until an appreciable layer of alloy material is smeared on to the steel surface. This is shown clearly in the photomicrographs of the tracks after 400 runs.

With the lead-base alloys the wear is relatively heavy. The track almost obliterates the lapping marks in the steel surface after a few hundred runs over the same track. It is evident that there is good adhesion between the alloys and the steel, and that the shearing does not occur in the junctions at the steel interface but within the bulk of the alloy itself. This is also borne out by the curling up of the worn fragments of alloy and their adhesion to the edge of the slider.

With the tin-base alloys the wear is relatively light. The track does not completely obliterate the lapping marks in the steel surface, even after the alloy has traversed the same track 400 times, and it is apparent that the shearing occurs very close to the steel surface itself. The friction, however, is as high as with the lead-base alloys, so that the adhesion between the steel surface and the alloys must be strong, but apparently not quite as strong as the shear strength of the junctions. The worn portion is brightly burnished, and there is practically no curling up of worn fragments of the slider.

The wear values of the bearing alloys are lower than those of their respective matrix alloys, but they are of the same order. It is evident, therefore, that for both types of alloys the general behaviour, the appearance of the track, and the actual values of the wear of the bearing alloys are very similar to those of the corresponding matrix alloys. On the other hand, the lead-base alloys wear very much more rapidly than the tin-base alloys.

(v) *Lubricated Surfaces.*

It has been shown that the friction of metal surfaces is determined by the area of real contact A, and the shear strength s, of the metallic junctions. It is clear, however, that in general the strength of the junctions will depend on the intimacy of contact and strength of adhesion of the metals at the points of real contact. This, in turn, will be greatly influenced by the presence of surface films.

In an earlier paper (Bowden and Tabor, 1942*a*) it was shown that, with a particular metallic junction, or point of contact between metal surfaces, two conditions may obtain:—

(1) The strength of adhesion between the soft metal and the hard may be greater than the shear strength of the soft metal. In this case, the break will occur within the soft metal, and fragments will be left adhering to the surface of the hard one. If the fraction of the total area of contact over which this occurs be a, the frictional resistance due to these junctions will then be $s_1 a A$, where s_1 is the shear strength of the softer metal and A is the real area of contact.

(2) The strength of adhesion at the junction is less than the shear strength of the softer metal. In this case, the break will occur between the metals, and the soft metal will not be wiped on to the harder one. The value for the shear strength of these weaker junctions will not necessarily be constant. It may vary from a value that approaches s_1 down to very small values. Let s_2 be the average value. Over the whole area of contact there will, in general, be junctions of both types, and the total shearing force S will be—

$$S = A\,(s_1 a + (1-a)\,s_2).$$

Under most experimental conditions, metal surfaces are covered with a thin oxide layer, and other contaminating films. During sliding, these films are torn, many of the surface irregularities penetrate through them, and some metallic contact does occur. We should expect the fraction to be less than unity, and the adhesion and shear strength of the junctions, on the whole, to be less than that of the pure metals. Earlier experiments have shown that this is indeed so. If the surface films are removed by outgassing in high vacuum (Bowden and Hughes, 1939), the friction increases considerably, and values of $\mu = 6$ have been observed, for example, for outgassed nickel or tungsten.

With soft metals, however, there is considerable distortion of the surfaces, and the breakdown of these surface films is very marked. As a result, the adhesion is good over most of the area of contact, and the

fraction a becomes nearly equal to unity; shearing takes place within the softer metal itself, and the mean shear strength of the junctions becomes approximately equal to the shear strength s_1 of the softer metal.

On the other hand, the deliberate addition of suitable lubricant films to the metals diminishes the intimacy of contact and the strength of adhesion at the junctions. As a result, there is a marked reduction in friction and in the amount of metallic seizure and tearing. With the "matrix" alloys, for example, lubricated with mineral oil, the original crystalline surface is still clearly visible in the track. Although the surface is appreciably deformed by the passage of the steel slider, the amount of seizure and tearing has been greatly diminished. However, a certain amount of metallic adhesion has occurred, as may be seen from the fine parallel scratches in the track. As the slider passes repeatedly over the same track, the amount of tearing and smearing increases cumulatively, until after twenty runs the original crystalline structure has been obliterated.

A similar effect is observed with the bearing alloys. The arrangement of the hard crystallites is clearly visible in the track, and it is apparent that, although the surface has been deformed by the passage of the steel slider, the tearing and smearing of the matrix material has been very greatly reduced. Even after twenty traversals of the same track, the crystallites are still visible through the thin film of smeared and torn matrix material.

It is clear that the presence of the lubricant film has greatly reduced the extent of metallic seizure. It is true that a certain amount of metallic adhesion and tearing has occurred where the surface irregularities on the steel slider have torn through the lubricant film. Nevertheless, the total area over which this metallic seizure has taken place is very much smaller in the presence of the lubricant film than in its absence. It is indeed probable that the main effect of adding a lubricant is to reduce both the area of intimate metallic contact (determined by a) and the shear strength, s_2, of the junctions.

(vi) *Effect of Repeated Sliding Over the Same Track, Lubricated Surfaces.*

Continuous traversals of the same track do not produce any marked change in the friction. With the pure metals and the matrix alloys this is to be expected. The area of contact remains essentially unchanged, and the junctions formed are still of the same nature as in the first run.

With the bearing alloys, the fact that the friction for the first run, when the crystallites are still clearly visible in the track, is almost the same as for the hundredth run, when the crystallites have been almost completely wiped over by the smeared matrix material, is strong evidence for the view that the friction is determined essentially by the properties of the matrix material.

(vii) *Effect of Temperature, Lubricated Surfaces.*

The effect of temperature on the boundary lubricating properties of lubricants has been discussed in previous papers (Tabor, 1940, 1941). The breakdown of the lubricant is associated with a melting or

disorientation of the protective film formed by the lubricant on the metal surface. It is markedly dependent on the composition and structure of the sliding surfaces.

The results show that for lubricated surfaces the frictional properties with respect to temperature of the lead matrix alloy and of the lead bearing alloy are very similar. This applies when the lubricant is a mineral oil or pure stearic acid. This again suggests that the friction is determined essentially by the properties of the matrix material itself.

With the tin-base alloys there is also a similarity in behaviour between the matrix alloy and the bearing alloy, but the similarity is not as close as with the lead-base alloys.

7. Conclusions.

The results discussed in this paper provide additional support to the theory of metallic friction proposed in earlier work. According to this view, the friction between metal surfaces is due primarily to the shearing of metallic junctions formed at the points of contact, and to the force required to drag the surface irregularities of the harder surface through the softer one. When the ploughing term is small, the friction is determined by the real area of contact, and the shear strength of the junctions. For clean surfaces, where the adhesion between the metals is good, the shearing usually takes place within the softer metal, and the friction depends upon the shear strength of the softer metal itself. When the surfaces are contaminated, either with oxide films or lubricants, the total area of contact is essentially unchanged, but the amount of metallic contact is reduced and the strength of the junctions is diminished. As a result the friction is lowered.

With clean metal surfaces it is not, as a rule, possible to reduce the friction by using a metal of low shear strength, since such a metal is usually soft and gives a comparatively large area of contact. For this reason, most "clean" metals give a high co-efficient of friction of the order of $\mu = 1$. A small value of shear strength and area of contact may, however, be achieved by depositing a thin film of a soft metal on a hard one. The hard surface supports the load, giving a small area of contact, whilst the shearing takes place within the thin film of the softer metal (low shear strength). Under these conditions it is possible to obtain extremely low co-efficients of friction for clean metal surfaces. Earlier work has indeed shown that a large class of bearing alloys function by the extrusion and smearing of a thin film of a soft constituent over the surface of a harder matrix. This mechanism applies to bearing alloys of the copper-lead type, which consist of a hard metal matrix with a softer metal finely dispersed through it.

With the typical white-metal bearing alloys discussed in this paper, the results show repeatedly the similarity between the bearing alloys and their respective matrix alloys. The friction, when clean and lubricated, the behaviour with respect to temperature and wear, the types of track formed, and the nature of wear, are all markedly alike. These properties are also similar to those of pure lead and pure tin,

except that, in general, the friction of the alloys is less than that of the pure metals. It is evident, therefore, that the behaviour of the bearing alloys is similar to that of materials containing no hard crystallites.

A survey of the main results in this paper (summarized in Table 13) indicates that, in general, the friction of the bearing alloys is less by a few per cent. than that of the corresponding matrix alloys. This difference may be due to the presence of the hard crystallites in the bearing alloys. On the other hand, it is extremely difficult to reproduce in a separate matrix alloy the complex phase relationships existing in the matrix of the bearing alloy. This difference in friction may, therefore, be due to differences in the constitution and structure of the matrix alloy and the matrix material of the bearing alloy. The difference in frictional behaviour, however, is small, and it is apparent that the hard crystallites do not greatly affect the intrinsic frictional or wear properties of the bearing alloys.

With the tin-base alloys, however, there is some divergence in frictional behaviour for lubricated surfaces, particularly at elevated temperatures. At these temperatures, indeed, the frictional behaviour of the matrix alloy is intermediate between that of the bearing alloy and of pure tin. It is, of course, possible, as has been indicated above, that slight changes in the composition of the matrix alloy might bring its frictional properties in closer line with those of the bearing alloy. It is, however, possible that with the tin-base bearing alloys the hard acicular crystallites may play a more important part in determining its basic frictional properties.

Table 13.—Summary of Main Results at Room Temperatures.

Surface.	Co-efficient of Friction (μmax.) at Room Temperature.			Wear for 3,000 cm. Track, Clean.
	Clean.	Mineral Oil.	Stearic Acid.	
				mg.
Steel on lead bearing alloy ..	0·4–0·5	0·12	0·08	..
Steel on lead matrix alloy..	0·4	0·15	0·06–0·09	..
Lead bearing alloy on steel ..	0·5	0·3	..	8–11
Lead matrix alloy on steel ..	0·7	0·35	..	11–14
Steel on tin bearing alloy ..	0·7	0·13	0·07	..
Steel on tin matrix alloy ..	0·7–0·8	0·13	0·09	..
Tin bearing alloy on steel ..	0·7	0·35	..	0·2
Tin matrix alloy on steel ..	0·8	0·4	..	0·3–0·7

In spite of the reservations made concerning the behaviour of the tin-base alloys it is clear that, in general, the frictional behaviour of the bearing alloys is determined essentially by the properties of the matrix material in them. According to this view, the load is supported mainly by the matrix. The pressure and motion of the steel surface impress the hard crystallities deeper into the matrix and cause an extrusion and smearing of the matrix material over the surface of the alloy. Welding takes place between the steel surfaces and the matrix material and the shearing takes place within metallic junctions composed of the matrix

material itself. When clean surfaces are used, this smearing and tearing of the matrix material over the surface of the track completely obliterates the arrangement of the hard crystallites. When a lubricant is used, the seizure and smearing is far less and this process is much more gradual. For both clean and lubricated surfaces, the hard crystallites play no appreciable part in the frictional behaviour of the alloys.

In practice, however, it is not only the frictional and the wear properties which determine the suitability of an alloy as a bearing metal. It is evident that many of the mechanical properties, such as the hardness and its variation with temperature, the compressive strength, and the resistance to mechanical fatigue, may all play a vital part in the practical performance. It is true that the hardness of the matrix alloys is of the same order as that of the bearing alloys. But it is about 20 per cent. lower (measured in Brinell units), and this difference may be of great importance. It is also possible that there may be important differences in the other mechanical properties, particularly at high temperatures. For example, recent work by Boas and Honeycombe has shown that the presence of hard particles in a softer matrix may "stiffen" the whole alloy and increase its resistance to "thermal fatigue". It is possible, therefore, that some of the significant differences in the mechanical properties of the bearing alloys and the matrix alloys may be due, in part, to the presence of the hard crystallites.

Nevertheless, the evidence supports the view that the hard crystallites make little essential contribution to the *basic frictional* properties of the bearing alloys. They may, however, play a small but significant role in imparting superior mechanical and physical properties to the alloy under practical running conditions.

8. Comparison between Lead-base and Tin-base Alloys.

A point of some interest is the comparison between the lead-base and tin-base alloys. The frictional properties of the lead bearing alloy when clean and when lubricated, at room temperature and at elevated temperatures, are generally slightly better than those of the tin bearing alloy. However, its wear on steel surfaces is very much heavier. Its hardness (measured in Brinell units) is also about 15 per cent. less. Apart, therefore, from the question of mechanical properties which may play a vital role in the practical behaviour of a bearing, the lead bearing alloy should, in practice, be at least as satisfactory as the tin alloy, from the point of view of its frictional behaviour. Under severe conditions, however, the rate of wear of the lead bearing alloy may be very much higher.

9. Acknowledgments.

I wish to express my thinks to Dr. Bowden for his helpful discussion at many points of the investigation, and to Mr. R. W. K. Honeycombe for his assistance in the preparation of several alloys and for his general advice on certain metallurgical aspects of this work.

I also wish to thank Mr. J. N. Gregory for making some of the earlier frictional measurements.

10. References.

Bassett, H. N. (1937).—"Bearing Metals and Alloys." (London: Edward Arnold and Co.).

Bowden, F. P., and Hughes, T. P. (1939).—*Proc. Roy. Soc.* A. **172**: 263.

Bowden, F. P., and Leben, L. (1939).—Ibid. **169**: 371.

Bowden, F. P., and Leben, L (1940)—*Phil Trans.* A.**239**: 1.

Bowden, F. P., Leben, L., and Tabor, D. (1939).—*Engineer* **168**: 214.

Bowden, F. P., and Ridler, K. E. W. (1936).—*Proc. Roy. Soc.* A. **154**: 640.

Bowden, F. P., and Tabor, D. (1942*a*).—Coun. Sci. Ind. Res. (Aust.), Bull. 145, Paper 1.

Bowden, F. P., and Tabor, D. (1942*b*).—Coun. Sci. Ind. Res. (Aust.), Bull. 145, Paper 2.

Bowden, F. P., and Tabor, D. (1942*c*).—Coun. Sci. Ind. Res. (Aust.), Bull. 155.

Desch, C. H. (1937).—"Metallography." 4th Ed. (New York: Longmans, Green and Co. Ltd.).

Gregory, J. N. (1943).—Coun. Sci. Ind. Res. (Aust.), Lubricants and Bearings Report No. A.74 (mimeo.).

Hughes, T. P., and Whittingham, G. (1942).—*Trans. Farad. Soc.* **38**: 9.

Matthew, —. (1940).—*J. Roy. Tech. Coll. Glasgow* **4**: 360.

Sampson, J. B., Morgan, F., Reed, D. W., and Muskat, M. (1943).—*J. Appl. Phys.* **14**: 689.

Tabor, D. (1940).—*Nature* **145**: 308.

———— (1941).—Ibid. **147**: 609.

PLATE 1.

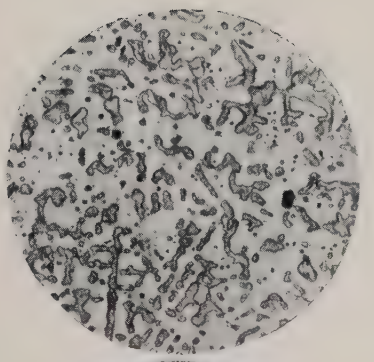

FIG. 1 (×200).—Non-dendritic copper-lead alloy. The lead particles, shown as the darker constituent, are dispersed throughout the hard copper matrix.

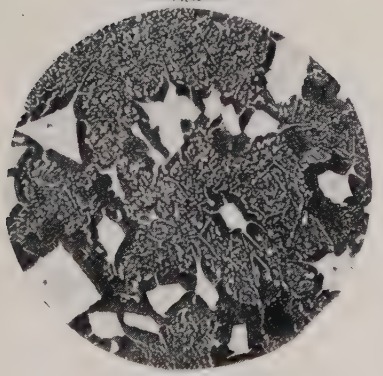

FIG. 2 (×200).—Lead bearing alloy. This consists of a lead-tin-antimony eutectic (the fine duplex structure) in which are dispersed the hard cuboids of tin-antimony compound. The dark areas surrounding the cuboids consist of a lead-rich solid solution. The matrix consists of the eutectic and the solid solution.

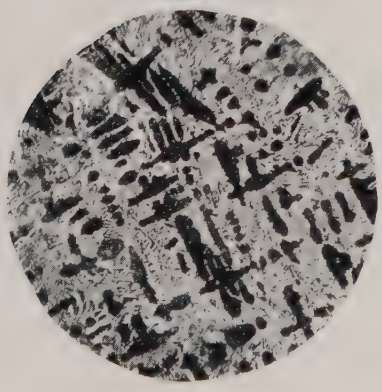

FIG. 3 (×200).—Lead "matrix" alloy. The dark areas are dentrites of lead-rich solid solution. The background possessing the fine duplex structure, is a lead-tin-antimony eutectic. This alloy is similar in composition to the matrix material of the lead bearing alloy and its structure, consisting of lead-rich solid solution dispersed in the lead-tin-antimony eutectic, approximates to the structure of the matrix. There are no hard particles present.

PLATE 2.

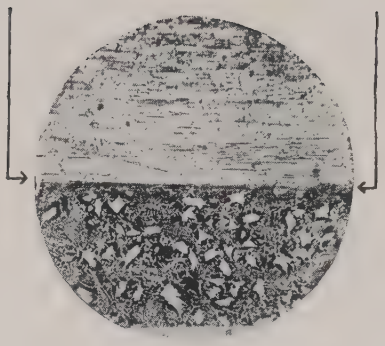

FIG. 1 (×66).—Portion of track formed in lead bearing alloy when clean, after steel slider has passed over the surface once. It is seen that the structural arrangement of the hard tin-antimony cuboids has been completely obliterated by the passage of the steel slider.

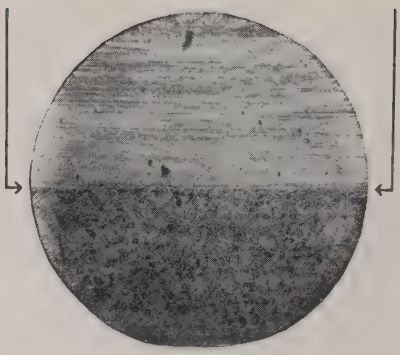

FIG. 2 (×66).—Portion of track formed in lead "matrix" alloy when clean, after steel slider has passed over the surface once. It is seen that the crystalline arrangement of the surface has been badly damaged by the passage of the steel slider.

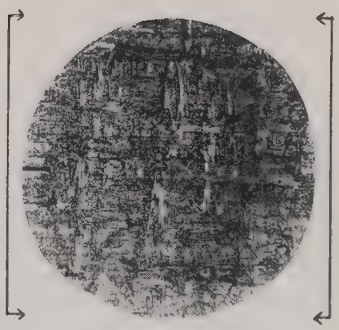

FIG. 3 (×66). — Track formed by lead bearing alloy after traversing the same steel surface 400 times (unlubricated). The smearing of the alloy is very marked and completely obliterates the lapping marks in the steel surface.

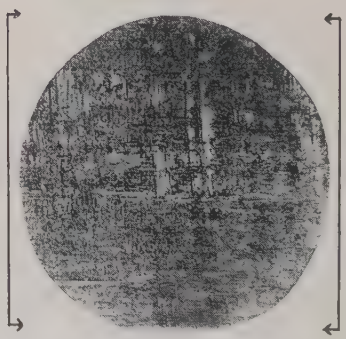

FIG. 4 (×66).—Track formed by lead "matrix" alloy after traversing the same steel surface 400 times (unlubricated). The smearing of the alloy is very marked and completely obliterates the lapping marks in the steel surface.

PLATE 3.

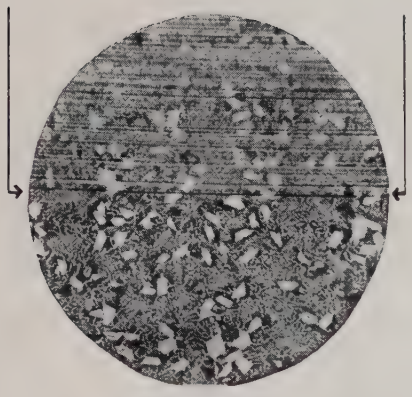

FIG. 1 (×75).—Portion of track formed on lead bearing alloy. First run, lubricated with mineral oil. The arrangement of the hard tin-antimony cuboids has been very little disturbed by the passage of the steel slider. The smearing of the track has been greatly reduced by the presence of the lubricant. Compare with Plate 2, Fig. 1.

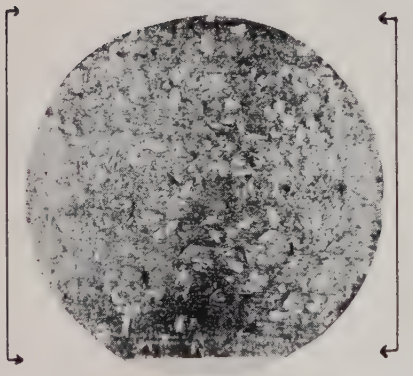

FIG. 2 (×75).—Central portion of track on lead bearing alloy. Twentieth run, lubricated with mineral oil. The tin-antimony cuboids are still clearly visible in the surface of the track.

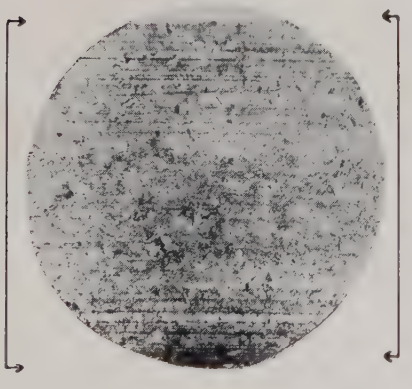

FIG. 3 (×75).—Central portion of track on lead bearing alloy. Hundredth run, lubricated with mineral oil. The hard crystallites have been almost completely obliterated by the repeated passage of the steel slider.

PLATE 4.

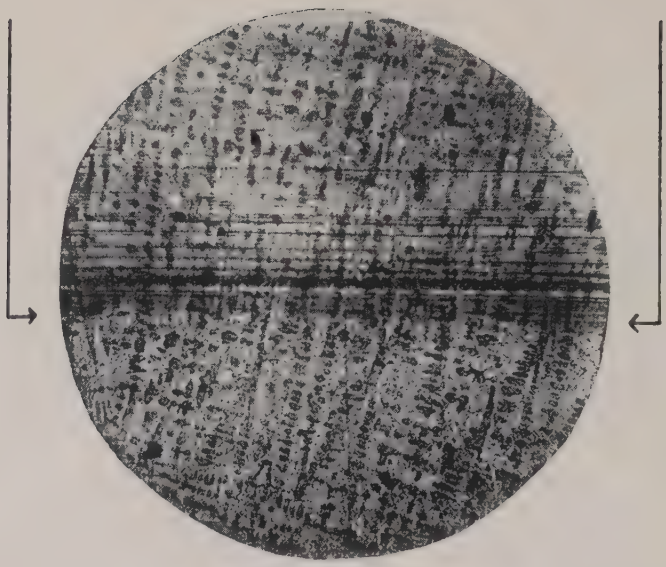

Fig. 1 (×110).—Portion of track formed on lead "matrix" alloy. First run, lubricated with mineral oil. The crystalline arrangement of the surface has been very little disturbed by the passage of the steel slider, and the smearing has been greatly reduced. Compare with Plate 2, Fig. 2.

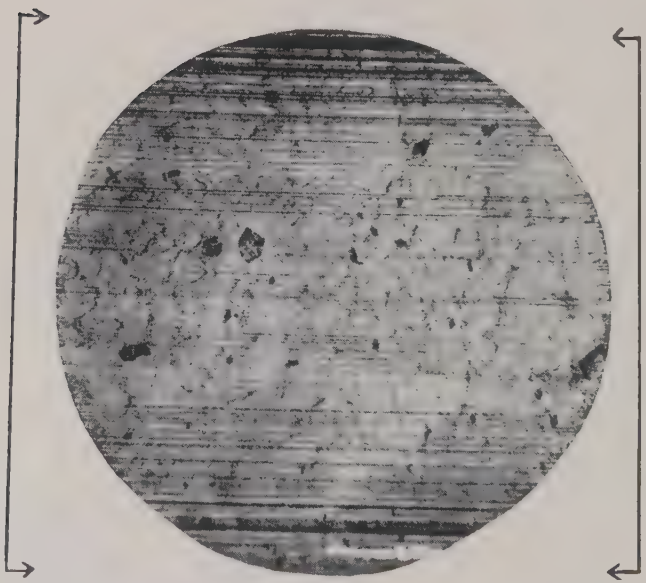

Fig. 2 (×110).—Central portion of track on lead "matrix" alloy. Twentieth run, lubricated with mineral oil. The structure of the surface has been almost completely obliterated by the passage of the steel slider.

PLATE 5.

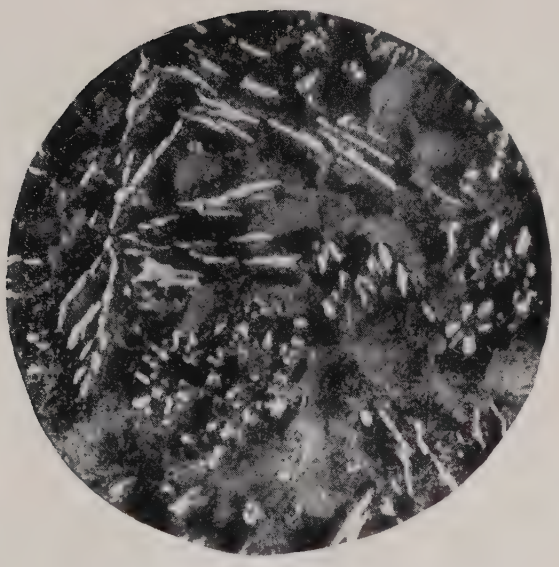

Fig. 1 (×300).—Tin bearing alloy. This consists of a tin-rich solid solution (the matrix) in which are embedded the hard acicular crystallites of copper-tin compound.

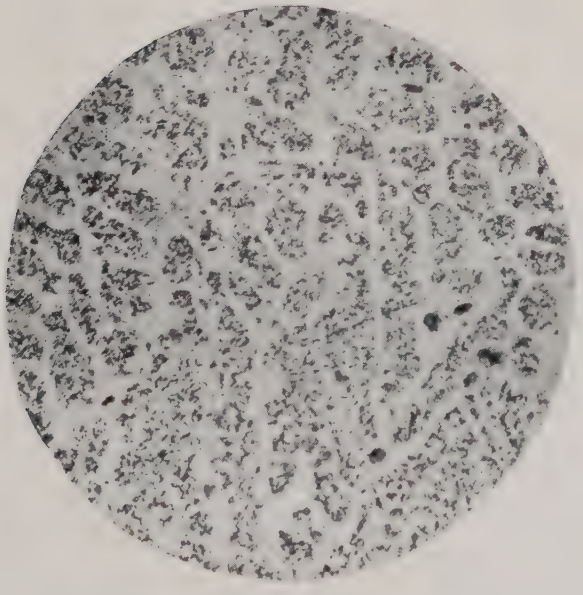

Fig. 2 (×300).— Tin "matrix" alloy. This consists of a tin-rich solid solution. The dark patches are probably micro-segregations. This alloy is similar in composition to the matrix material of the tin-base bearing alloy shown in Fig. 1 above. There are no hard crystallites present.

PLATE 6.

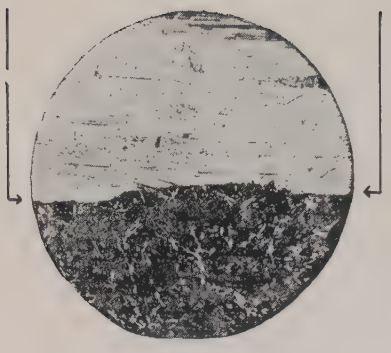

Fig. 1 (×66).—Portion of track formed in tin bearing alloy when clean, after steel slider has traversed the surface once. It is seen that the structural arrangement of the hard needles of copper-tin compound has been completely obliterated by the passage of the steel slider.

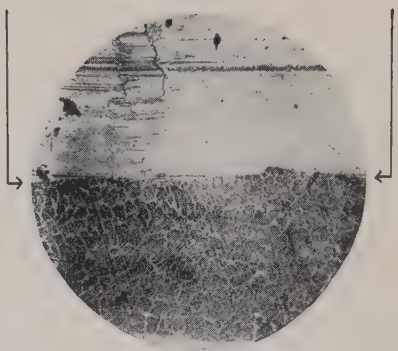

Fig. 2 (×66).—Portion of track formed in tin "matrix" alloy when clean, after steel slider has traversed the surface once. It is seen that the crystalline arrangement of the surface has been badly damaged by the passage of the steel slider.

Fig. 3 (×66).—Track formed by tin bearing alloy after traversing the same steel surface 400 times. The smearing of the alloy is appreciable, but the lapping marks in the steel surface are still visible.

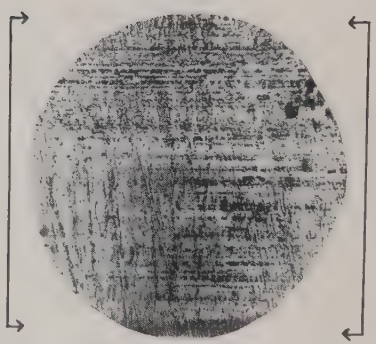

Fig. 4 (×66).—Track formed by tin "matrix" alloy after traversing the same steel surface 400 times. The lapping marks in the steel surface are still visible through the smeared alloy.

PLATE 7.

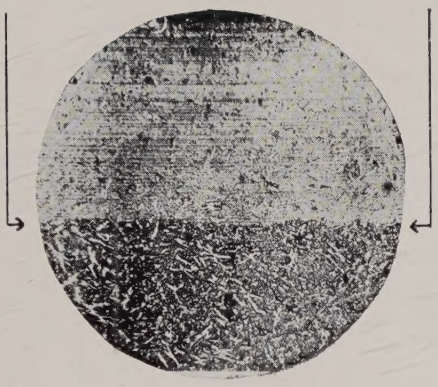

Fig. 1 (×75).—Portion of track formed on tin bearing alloy. First run, lubricated with mineral oil. The arrangement of the hard needles of copper-tin compound has been very little disturbed by the passage of the steel slider. The smearing of the track has also been greatly reduced by the presence of the lubricant. Compare with Plate 4, Fig. 1.

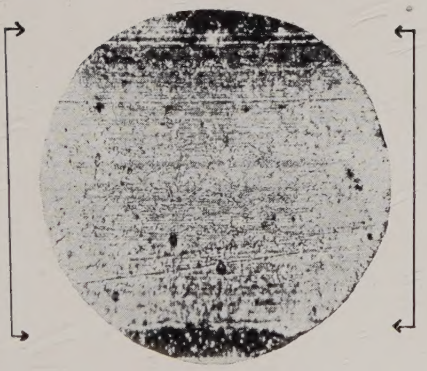

Fig. 2 (×75).—Central portion of track on tin bearing alloy. Twentieth run, lubricated with mineral oil. The hard copper-tin needles are still visible in the surface of the track.

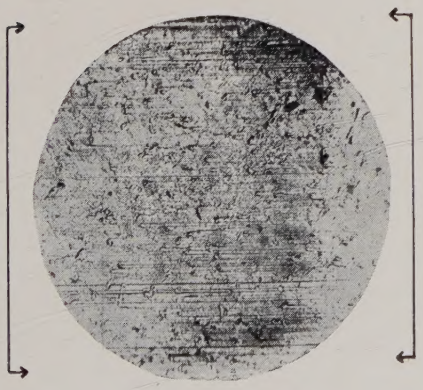

Fig. 3 (×75).—Central portion of track on tin bearing alloy. Hundredth run, lubricated with mineral oil. The hard crystallites are still visible, but are gradually being obliterated by repeated traversals of the steel slider.

PLATE 8.

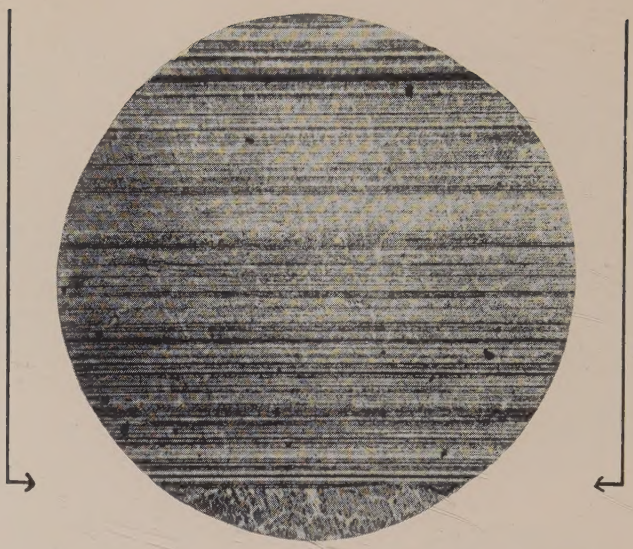

Fig. 1 (×110).—Portion of track formed on tin "matrix" alloy. First run, lubricated with mineral oil. The crystalline arrangement of the surface is still visible in the track. The surface has been little disturbed by the passage of the steel slider, and the smearing has been greatly reduced. Compare with Plate 4, Fig. 2.

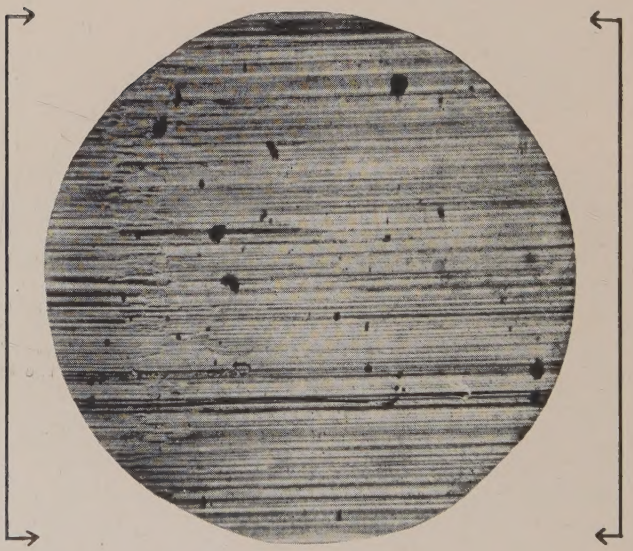

Fig. 2 (×110).—Central portion of track on tin "matrix" alloy. Twentieth run, lubricated with mineral oil. The structure of the surface has been completely obliterated by the passage of the steel slider.

J. J. Gourley, Government Printer, Melbourne.

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numbered from 140 onwards.

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142. A Soil and Land Use Survey of the Hundreds of Riddoch, Hindmarsh, Grey, Young, and Nangwarry, County Grey, South Australia
143. Production of Dried Grapes in Murray Valley Irrigation Settlements. 1.—Viticulture
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145. Friction and Lubrication: Report No. 1
146. An Analysis of the Outbreaks of the Australian Plague Locust (Chortoicetes terminifera Walk.) during the Seasons 1937-38 and 1938-39
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158. The Recovery of Inter-block Information in Quasi-Factorial Designs with Incomplete Data. 1.
159. Poisonous and Harmful Fishes
160. The Outbreak of the Australian Plague Locust (Chortoicetes terminifera Walk.) in the Season 1939-40, with Special Reference to the Influence of Climatic Factors
161. A Review of the Evidence Concerning Expansive Reaction between Aggregate and Cement in Concrete
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163. Transmission of Potato Virus Diseases. Parts 1 and 2
164. Studies in the Biology of the Skin and Fleece of Sheep. Parts 1, 2, and 3
165. Potato Virus X.: Mixtures of Strains and the Leaf Area and Yield of Infected Potatoes
166. Fertility in Sheep. An Experimental Study of Periodicity of Oestrus and Non-breeding Seasons in Australia
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170. Pea Mosaic on Lupinus varius L. and other species in Western Australia
171. Experiments with Insecticides against the Red-legged Earth Mite (Halotydeus destructor (Tucker)).

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172. Zebu-cross cattle in Northern Australia. An Ecological Experiment
173. The Detonation of High Explosives by Impact
174. Recent Advances in the Prevention and Treatment of Blowfly Strike in Sheep
175. The Recovery of Inter-block Information in Quasi-Factorial Designs with Incomplete Data. 2.
176. The Analysis of Cubic Lattice Designs in Varietal Trials
177. A Soil Map of Australia
178. Food Composition Tables
179. Lubrication between the Piston Rings and Cylinder Wall of a Running Engine
180. Studies on Deglutition in Sheep. Parts 1 and 2
181. Sheep Blowfly Investigations. The Attractiveness of Sheep for Lucilia cuprina
182. The Effectiveness of Various Mineral Dusts for the Control of Grain Pests
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195. An Account of Experiments Undertaken to Determine the Natural Population Density of the Sheep Blowfly, Lucilia cuprina Wied.
196. Transmission of Potato Virus Diseases. Part 5
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198. Plant Responses to Molybdenum as a Fertilizer. Parts 1 and 2
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